Interruption of machine milking in dairy cows: effects on intramammary pressure and milking characteristics

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SUMMARY. Experiments were designed to test the hypothesis that milk ejection rate decreases during milking, thereby causing insufficient refill of the cistern and decreasing milk flow rate towards the end of milking. In a first series of experiments machine milking of the left front quarters of 11 cows was interrupted for 2 min after removal of 25, 50 or 75% of expected total milk yield, while milking was continued in the other three quarters. Milk flow was recorded during machine-on times. Intramammary pressure (IMP) was recorded during premilking teat stimulation and during interruption of milking. IMP during interruption of milking decreased with decreasing amounts of milk remaining in the udder. The IMP did not change during these interruptions when they occurred after 25 and 50% of expected total milk yield was removed. Thus, the ejection rate could keep up with the milk flow or removal rate. However, IMP increased during interruption of milking following removal of 75% of total yield, although significantly so only in cows with a high milk flow rate. Obviously, more milk was removed than was transported to the cisternal cavity. It is likely that a reduced ejection rate caused the decreased milk flow rate. In a second series of experiments the pulsation ratio of the milking machine was changed from the usual 70:30 to 50:50 with the aim of reducing the milk flow rate and thus adapting to the ejection rate at the end of milking. The changed pulsation ratio caused a reduced peak flow rate and a prolonged high milk flow period, whereas the main flow rate did not change significantly.

The main fraction of milk stored in the mammary gland, the alveolar milk, is fixed by adhesive and capillary forces and must be actively shifted into the cisternal cavity by the milk ejection reflex to become available for removal. Premilking teat stimulation causes enhanced oxytocin release and increased intramammary pressure (IMP) within the cistern up to a physiological maximum (Gorewit, 1979; Mayer *et al.* 1991; Bruckmaier *et al.* 1994). Oxytocin release occurs not only at the start, but continues throughout the whole milking (Mayer *et al.* 1984; Schams *et al.* 1984). However, although maximal IMP is reached, the alveolar milk is not completely ejected during prestimulation and early milking. Alveolar milk ejection lasts throughout the entire milking and continuously elevated concentrations of oxytocin are necessary for continuous and complete milk removal (Bruckmaier *et al.* 1994). It seems therefore possible that the milk flow rate during machine milking is limited not only by anatomical characteristics of cisterns and teats, and smooth muscle tone in

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the teat and around the cistern and large ducts (Andreae, 1958; Williams & Mein, 1987), but also by the rate of alveolar milk transfer into the cisternal cavity during milking.

The aim of this work was to test the hypothesis that milk ejection rate decreases during milking, resulting in an insufficiently rapid refilling of the cisternal cavity. If so, it was theorized that a compensatory increase of IMP would occur during interruption of milking.

In addition, the hypothesis was tested that ejection rate can more easily adapt to milk flow rate if the pulsation ratio is lowered. For this purpose, experiments were designed in which peak flow rates (PFR) were reduced, but the main flow rate was not affected.

MATERIALS AND METHODS

Cows

All experimental cows were from the herd of the Swiss Federal Research Station for Animal Production, Posieux: Simmental × Red Holstein and Swiss Braunvieh × Brown Swiss breeds with an average milk yield of 7300 kg/year. Cows were kept in tie stalls and fed maize silage, hay and concentrates according to their individual production levels. Experiments were performed during routine milking from 16.00 to 18.00.

Recording of milk flow and intramammary pressure

Milking was performed at a vacuum level of 45 kPa and a pulsation rate of 60 cycles/min. Milk flow was continuously recorded using a strain gauge system and a strip chart recorder as described by Schams *et al.* (1984). Table 1 defines the various milking traits investigated. PFR is defined as maximum milk flow lasting for at least 10 s, and main flow rate as milk removed until stripping divided by the corresponding milking time.

IMP was measured by a strain gauge system via a cannula through the teat canal and was continuously conveyed to a strip chart recorder as described by Bruckmaier *et al.* (1994). The pressure was calibrated to zero at the level of the teat base.

Experiment 1

Eleven cows in weeks 11–23 of their first to fourth lactation were milked at a 65:35 pulsation ratio. Teatcups (Alfa Laval; Harmony, S-147 21 Tumba, Sweden) were connected with a quarter milking claw (Surge RX; Babson Bros & Co., Naperville, IL 60563, USA). Milk yield and milk flow of the left front quarter were recorded separately and those of the other three quarters were measured together.

The IMP was recorded in the left front quarter. Manual stimulation was applied until IMP reached its maximum. Milking was started subsequently. After 25, 50 or 75% of the expected milk yield (as assessed on preceding evening milkings) had been collected, milking of the left front quarter was interrupted for 2 min. During this period IMP was measured, while milking of the remaining quarters continued. After the interruption, milking was resumed and continued until the udder was emptied. Amounts of milk removed before the interruption were measured and expressed as percent of total yields (M1(1/4), Table 2). For interruptions between 5–35, 35–65 and 65–95% of the actual milk yield, results were classified as 25, 50 and 75% respectively.

In control milkings, IMP was recorded in the left front quarter before and during manual stimulation, which was applied until IMP reached a maximum. Subsequently

Table 1. *Milking characteristics and intramammary pressure traits*

M1(1/4)	kg	Milk yield in the left front quarter until interruption of milking
M2(1/4)	kg	Milk yield in the left front quarter after interruption of milking
M(1/4)	kg	Total milk yield in the left front quarter
PFR1(1/4)	kg/min	Peak flow rate until interruption of milking (left front quarter)
PFR2(1/4)	kg/min	Peak flow rate after interruption of milking (left front quarter)
ΔPFR(1/4)	kg/min	Difference between PFR2(1/4) and PFR1(1/4) (left front quarter)
MPFR(1/4)	kg/min	Maximum peak flow rate in the left front quarter (either PFR1(1/4) or PFR2(1/4))
M(3/4)	kg	Milk yield in the three non-interrupted quarters
PFR(3/4)	kg/min	Peak flow rate in three non-interrupted quarters
M(4/4)	kg	Total milk yield
IMP	kPa	Intramammary pressure
BP	kPA	Baseline pressure, IMP recorded before milk ejection
EP	kPa	Ejection pressure, maximum IMP after manual teat stimulation and before milking
IP	kPa	Interruption pressure, IMP just after interrupting the milking
IP−EP	kPa	IMP change until interruption of milking
ΔIP	kPa	IMP change during interruption of milking

the other three quarters were milked, while IMP recording in the left front teat continued. After milk flow of the three quarters had dropped below 150 g/min, IMP recording was stopped. Thereafter, the left front quarter was immediately milked.

Experiment 2

Nineteen animals in weeks 3–32 of their first to eighth lactation were milked at pulsation ratios of 50:50 and 70:30. A 1 min manual teat stimulation was applied before milking. Milk flow of all quarters together was recorded continuously. After milk flow had dropped below 200 g/min the udder was emptied by machine stripping.

Evaluation of results and statistical analyses

Results are presented in text and Tables as means ± SE. For statistical evaluations the SAS program package, release 6.08 (SAS, 1990), was used. Means of different classes and groups were tested for significant differences ($P < 0{\cdot}05$) using the General Linear Model procedure and Student's t test. Changes during the course of one trial were tested for significance ($P < 0{\cdot}05$) by means of the paired t test.

In Expt 1 the animals were divided into two groups: cows with low three quarter PFR (PFR(3/4) ⩽ 3 kg/min) and cows with high three quarter PFR (PFR(3/4) > 3 kg/min). To assign the animals to one of the two PFR groups, the mean of the four experimental milkings (control and three interrupted milkings) was calculated. Pearson's coefficients of correlation between various traits were calculated. The repeatability ($w = \sigma^2(a)/(\sigma^2(a)+\sigma^2(e))$) was computed according to Essl (1987) employing the General Linear Model procedure based on estimated values: $s^2(a) = (\mathrm{MS}(a)-\mathrm{MS}(e))/n$ and $s^2(e) = \mathrm{MS}(e)$ where σ^2 is real variance, s^2 estimated variance, MS mean square, a animal, e error and n the number of animals. The model $Y = \mu+a_j+e_{ij}$ was used.

RESULTS

Experiment 1

Milking characteristics. The milk yield of the left front quarter (M(1/4)) was 25·8 ± 0·9 % of the total milk yield (M(4/4)) which was 9·73 ± 2·84 kg (Table 2). Milk yields were not significantly different between the three interrupted milkings and

Table 2. *Milking characteristics† and intramammary pressure before, during and after interruption of milking in cows with mean three quarter peak flow rates (PFR(3/4)) below and above 3 kg/min*

(Values are means ± SE)

Interruption class, %...		25		50		75	
Average M1(1/4), %...		28·5 ± 1·32		47·56 ± 2·61		78·02 ± 2·65	
Milk flow group (PFR(3/4)), kg/min...		⩽ 3·0	> 3·0	⩽ 3·0	> 3·0	⩽ 3·0	> 3·0
No. of observations...		4	7	5	7	6	8
Trait	Unit						
M(1/4)	kg	2·4 ± 0·5	2·6 ± 0·3	2·9 ± 0·3	2·5 ± 0·2	2·2 ± 0·3	2·4 ± 0·3
M1(1/4)	%	28 ± 1[a]	30 ± 3[A]	53 ± 3[b]	44 ± 3[B]	74 ± 5[c]	80 ± 4[C]
PFR1(1/4)	kg/min	0·6 ± 0·1*	1·0 ± 0·1	0·9 ± 0·2	1·2 ± 0·1	0·8 ± 0·1*	1·2 ± 0·1
PFR2(1/4)	kg/min	0·7 ± 0·1	1·1 ± 0·2[A]	0·9 ± 0·2	1·2 ± 0·1[A]	0·6 ± ·0·1	0·7 ± 0·1[B]
ΔPFR(1/4)	kg/min	0·1 ± 0·0[a]	0·1 ± 0·1[A]	0·0 ± 0·0[ab]	0·0 ± 0·1[A]	−0·2 ± 0·1[b]*	−0·5 ± 0·1[B+]
BP	kPa	1·3 ± 0·1	1·8 ± 0·5	1·7 ± 0·0	1·5·0·3	1·6 ± 0·1	1·5 ± 0·4
EP	kPa	4·3 ± 0·0	4·1 ± 0·8	4·1 ± 0·1	4·3 ± 0·5	4·2 ± 0·0	4·1 ± 0·5
IP	kPa	3·6 ± 0·2[a]	3·4 ± 0·5[A]	2·8 ± 0·1[ab]	3·2 ± 0·4[A]	2·5 ± 0·3[b]	1·7 ± 0·4[B]
ΔIP	kPa	−0·1 ± 0·0[a]	0·0 ± 0·1[A]	0·0 ± 0·1[a]	−0·1 ± 0·1[A]	0·1 ± 0·1[a]*	0·4 ± 0·1[B+]
IP−EP	kPa	−0·7 ± 0·2[a+]	−0·7 ± 0·3[A]	−1·3 ± 0·1[ab+]	−1·1 ± 0·2[A+]	−1·7 ± 0·3[b+]	−2·4 ± 0·4[B+]

† Characteristics are defined in Table 1.
* Means of milk flow classes were significantly different within interruption class: $P < 0{\cdot}05$.
[A,B,C] Means of interruption classes (milk flow > 3·0 kg/min) without common subscript letters were significantly different: $P < 0{\cdot}05$.
[a,b,c] Means of interruption classes (milk flow ⩽ 3·0 kg/min) without common subscript letters were significantly different: $P < 0{\cdot}05$.
\+ Values of ΔPFR(1/4), ΔIP and IP-EP were significantly different from zero: $P < 0{\cdot}05$.

controls. The repeatabilities of the three quarter and left front quarter milk yields (M(3/4) and M(1/4)), were 0·96 and 0·78 respectively.

Except for the high milk flow group, and then only if the interruption was at 75% of total milk yield, there was no significant difference between the PFR before and after interruption of milking and also no difference between the different interruption classes (PFR1(1/4) and PFR2(1/4); Table 2, Fig. 1). The repeatability for the three quarter PFR (PFR(3/4)) and PFR1(1/4) was 0·83.

Intramammary pressure. The time from the start of manual teat stimulation until maximal pressure (ejection pressure) was reached was 1·55 ± 0·06 min (Fig. 1).

The mean baseline pressure and the mean ejection pressure were 1·6 ± 0·1 and 4·2 ± 0·2 kPa respectively. In both cases, there were no significant differences between the three interrupted milkings and control, and their repeatabilities were 0·58 and 0·89 respectively. During control milkings ejection pressure decreased to 3·8 ± 0·2 kPa, but this change was not significant. The correlation between baseline pressure and the left quarter milk yield (M(1/4)) was 0·55.

The interruption pressure decreased from the 25% to the 75% interruption, i.e. the decremental change (ejection pressure − interruption pressure) increased (Table 2, Fig. 1). The correlation between interruption pressure and left front quarter milk yield after milking (M2(1/4), kg) was 0·76. The IMP did not change during interruption (ΔIP; Table 2, Fig. 1) at 25 and 50% of total milk yield, but increased if milking was interrupted at 75% of total yield; however, this was significant only in the high milk flow group.

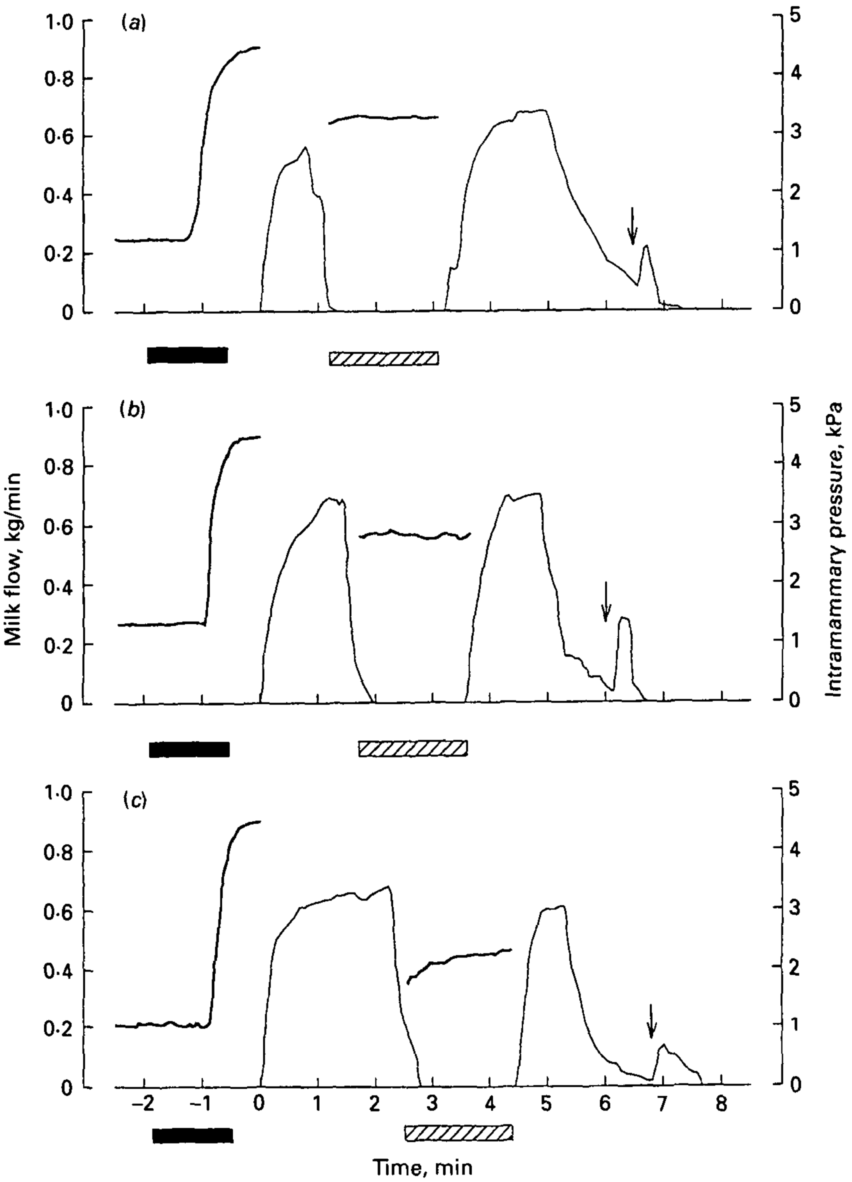

Fig. 1. ——, Milk flow and ——, intramammary pressure of the left front quarter of an individual cow before, during and after interruption of milking after removal of (*a*) 25%, (*b*) 50% and (*c*) 75% of the total milk yield. 0, Commencement of milking; ■, teat stimulation; ▨, intramammary pressure measurement in the left front quarter during interruption of milking; ↓, start of stripping.

Experiment 2

Milking time was significantly longer and PFR significantly lower if cows were milked at 50:50 than at 70:30 pulsation ratio (Table 3). Total and main milk yields and main flow rate were not significantly different between the two different pulsation ratios (Table 3). In Fig. 2 the two milk flow curves of one cow are shown as an example.

Table 3. *Milking characteristics with pulsation ratios of 50:50 and 70:30 (evening milking)*

(Values are means ± SE for $n = 19$)

Variable	Pulsation ratio 50:50	70:30
Total milk yield, kg	12·4±0·7	11·8±0·7
Main milk yield, kg	12·0±0·7	11·4±0·7
Stripping yield, kg	0·4±0·1	0·4±0·1
Main milking time, min	6·4±0·3*	5·4±0·2*
Peak flow rate, kg/min	3·0±0·2*	3·8±0·3*
Mean flow rate, kg/min	1·9±0·1	2·1±0·1

* Means for different pulsation ratios were significantly different: $P < 0{\cdot}05$.

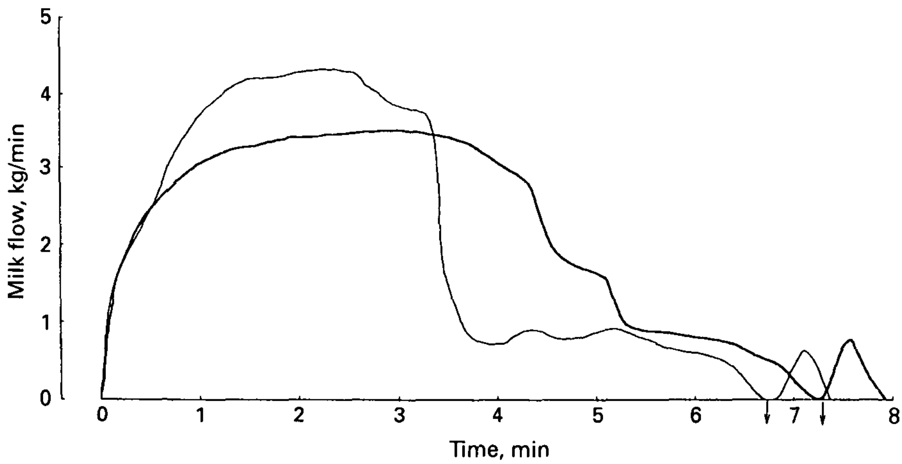

Fig. 2. Milk flow at a pulsation ratio of ——, 50:50 and ——, 70:30 for an individual cow. 0, Commencement of milking; ↓, start of stripping.

DISCUSSION

Repeatabilities of milk yield and PFR were very high, so the interruption of milking did not influence these traits.

The levels of baseline and ejection IMP in this study were similar to those previously measured (Mayer *et al.* 1991). During control milking the ejection pressure decreased slightly in the unmilked quarter during milking of the other quarters. It can be assumed that elevated oxytocin concentrations and myoepithelial contractions were maintained during the entire milking (Mayer *et al.* 1984; Bruckmaier *et al.* 1994). Therefore, the IMP should have been constant at its maximum level. The slight decrease in IMP was possibly due to evacuation and tissue relaxation of the other quarters and agrees with earlier findings (Whittlestone, 1955). There was some correlation between baseline pressure and the corresponding quarter milk yield. It is likely that the baseline pressure is generated mainly by the hydrostatic pressure of the cisternal milk. However, its repeatability was not very high, so there was presumably a considerable day-to-day variation in the amount of cisternal milk, whereas the milk yield was shown to be highly repeatable. Milk shifted from the alveolar compartment into the cistern in the absence of milk ejection was shown to increase with increasing time from the previous milking (Knight *et al.* 1994). Simultaneously, IMP in the cistern increases continuously (Bruckmaier, 1988).

The repeatability of ejection pressure was high and it was shown in earlier investigations that oxytocin release, which is caused by teat stimulation, forces alveolar milk into the cisternal cavity until the pressure increase within the teat cistern reaches a physiologically, anatomically and individually determined maximum (Mayer *et al.* 1991; Bruckmaier *et al.* 1991, 1994; Bruckmaier & Blum, 1992).

However, the ejection pressure was not correlated with milk flow rates. Furthermore, the milk flow was not influenced by the decrease in IMP (the difference between the interruption and ejection pressures), that is the PFR returned to the same level after as before milking interruption, except for the high milk flow group and only then if there was only a very small amount of milk left in the udder (75% interruption). Since the negative pressure of the milking vacuum is about 10-fold that of the IMP, it is likely that changes in IMP have no great influence on milk flow. Earlier investigations have shown that PFR is correlated with the extendibility of the teat canal (Andreae, 1958) and the muscle tone around the teat sphincter (Williams & Mein, 1987) and the mammary ducts, which are controlled by the adrenergic system (Roets *et al.* 1984; Roets & Peeters, 1985; Butler *et al.* 1992; Hammon *et al.* 1994). However, these investigations do not explain why the milk flow rate is decreasing towards the end of the milking.

No increase in IMP was observed when milking was interrupted at 25 and 50% of expected total yield, so obviously the milk ejection rate was sufficiently high to keep the mammary cistern filled.

However, a decreasing ejection rate is likely to occur, particularly toward the end of milking. The surface of the milk droplets in the alveoli is decreasing during milking, hence stronger contraction of the myoepithelial cells is needed for a constant milk ejection rate. It has been shown that the time from the start of stimulation and also the time from the start of IMP increase until maximal IMP is reached are dramatically prolonged if milk yield drops below 5 kg in late lactation (Bruckmaier, 1988; Bruckmaier *et al.* 1992). In cows with central inhibition of milk removal the time from oxytocin injection to commencement of milk flow was inversely correlated with the amount of milk actually removed in response to the injection of oxytocin (Bruckmaier *et al.* 1994). At the end of milking (interruption of milking at 75% of expected total yield) there was more milk removed by the milking machine than could be transported to the cisternal cavity. During interruption of milking the cistern was in part refilled, as indicated by an increase in IMP. This phenomenon was probably due to a delay in milk ejection rate as compared with milk flow, i.e. the milk removal rate towards the end of milking. As expected, this delay was especially pronounced in cows with a high milk flow.

By reduction of the pulsation ratio (from 70:30 to 50:50), the PFR was reduced and the duration of high milk flow prolonged while the main flow rate was not significantly altered. Obviously, the PFR could be adapted to the (alveolar) milk ejection rate for a prolonged period. This is in agreement with Thomas *et al.* (1991), who changed the pulsation ratio from 50:50 to 70:30. In their experiment the average flow rate increased slightly, while the 2 min milk yields increased by 23%. Mihina *et al.* (1990) developed equipment that could control the pulse frequency of milking machines in response to the ejection rate and, by using this, average milk flow was increased while maximum milk flow rate was slightly decreased.

In conclusion, reduced milk ejection rate has been demonstrated during late milking. Continuous adjustment of the milking machine characteristics such as pulsation ratio to the current milk ejection rate during the course of milking should theoretically equilibrate milk flow rate.

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